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Environmental Assessment of Two Waste Incineration Strategies for Central Norway

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Abstract

Background, Aims and Scope. A strategy of local incineration with 17 small incinerators (Scenario L) is compared to a strategy of 3 centralized waste incinerators (Scenario C) for the region of Central Norway, in order to assess differences in environmental performance. Rough calculations of costs are also included. The functional unit is the treatment of municipal, commercial and special waste not recycled, plus the heating of a specific number of households, for the period of 2002 to 2020.

Methods. Data on large and small scale incinerators were obtained from technology providers. LCA databases were used for transportation and heating, while cost estimates and Norwegian input-output tables were used for the construction of the facilities. The CML2 method was used to evaluate the impacts.

Results and Discussion. Transportation is a major contributor to aquatic toxicity and acidification as well as CO_2 emissions. Impacts from construction are considerable for photochemical oxidation, while incineration is important for terrestrial toxicity and CO_2 emissions.

Conclusion. Construction and operation of treatment facilities are, together with transportation, the main processes making a difference between the two strategies. Substantial gains will come from the reduction in transportation need when introducing a local incineration strategy. When considering a time span of two decades, the centralized scenario is about 2.5 to 5 times the impact potential of the local scenario for most impact categories, in terms of cumulative results. Cost estimates for the two solutions support these findings, as cumulated costs also favors a local solution.

Recommendation and Outlook. Transportation is a major contributor to several impact categories, and especially the transportation of special waste should become more efficient in terms of transportation distances. Cost estimates support the environmental assessment, but a more comprehensive economic study of the system would be valuable.

Keywords: LCA case studies; Norway; systems LCA; technology scenarios; waste incineration

Introduction

With increasing welfare, modern society generates an increasing amount of waste which in turn causes stress on the environment. To counter resource depletion and pollution it is important to regard waste as a resource. Both the EU Waste Framework Directive and the Norwegian waste management policy call for an increasing utilization of the materials or the energy contained in waste and for a reduction of the amount in landfills [1,2]. From the perspective of Industrial Ecology, materials recycling is preferred. But there always remains a significant fraction of the waste for which incineration is the preferred treatment option. In this work, LCA is used as a tool for comparing two alternative systems for future waste handling and energy recovery in Central Norway. This work does not focus on the specific technologies for energy production, but rather on the different ways of organizing energy systems for heat recovery of waste. Like other LCAs of energy systems, it is on the systems level [3]. The system boundaries are drawn to focus on the differences between the systems. In both of our scenarios the energy from the incineration of waste is utilized in district heating systems and industry. District heating systems distribute heat by hot water or steam to settlements and industry through pipes. Energy from waste incineration is thus utilized and offsets other sources of heat production, such as electricity, oil, natural gas etc. Water temperature can be adjusted according to outdoor temperature and demand. Central Norway already has a shortage of incineration capacity and the gap between available capacity and amounts of waste suitable for incineration will increase due to a projected growth in both the population and per capita waste generation. The amount of waste available for incineration will also grow due to the government policy to close old landfills. There is hence a need to expand incineration capacity in the region. The development of small scale incinerators for municipal and special waste makes it possible to develop a regional strategy for waste incineration based on local treatment. Technology suitable for local incineration of special waste has recently become available [4,5]. The scenarios developed in this study are assessed by combining a detailed waste flow model with LCA and environmental input-output analysis. Estimates for the economic costs are presented as well.

1 Scenarios

Two strategies for waste incineration are evaluated with respect to their environmental impacts. All waste types are accounted for. The geographical area under investigation is in both cases Central Norway, and the time span of the study is from 2002 to 2020. Scenario C represents a strategy of centralized incineration with large-scale incinerators, and scenario L a strategy of local treatment in small-scale installations. Both scenarios utilize the energy produced from

waste in district heating systems. The amount of waste, its origins and collection are the same in both systems. The systems differ in the technology used for treatment and the scale and number of incinerators. As a result, the need for bringing the waste to the incineration plants is higher for the centralized scenario, inducing more transportation. In Scenario C the special waste will mainly be taken care of in an existing treatment facility specially prepared for neutralizing and storing of such waste types, while about 5% of the amount will be incinerated for industrial purposes. This solution is based on the current situation in Central Norway. Scenario L, on the other hand, will make use of all the special waste for local incineration, due to new small scale incineration technology. Incineration of special waste is assumed to take place in plants dedicated to this type of waste only. These plants will be localized in central places in the region, since the amounts of special waste are not large enough for the same decentralized treatment as the other waste types. Costs related to this type of plants are also higher. It is therefore regarded as more reasonable to centralize these incinerators within the region.

The functional unit will be the treatment of all municipal, commercial and special waste produced within the region of Central Norway that is not recycled, i.e. available for incineration, plus the heating of a specific number of households for the period of 2002 to 2020. As mentioned above, only about 5% of special waste is incinerated in Scenario C, while the remaining is sent to a facility for neutralization and storing of special waste, hence heat production equivalent to that in Scenario L has to be added to fulfill the functional unit. Additional heat production is provided by natural gas production for utilization in district heating systems.

2 Method

Sources of waste generation and their sizes were identified for the region of Central Norway by using projections of population growth and waste generation. Having identified the sources, the next step is to establish sinks, i.e. facilities for the treatment of waste. The location, size and type of sinks are the main differences between the two scenarios. The environmental impact of the treatment facilities and transport are assessed using LCA. In order to utilize the energy content in the waste as heat in a district heating system, there has to be a sufficient need and number of customers located in the vicinity of the incineration plant. Growth in population and heat demand for the different parts of Central Norway are estimated for the entire time span to see whether there exists a reasonable demand for the potential heat output related to the amounts of waste produced. The projections are based on [4,6–9]. The region consists of about one hundred municipalities, and most of these have formed inter-municipal companies for collaboration on waste handling. These companies constitute the basis for the different projections as well as the structure for the planning of district heating systems. Amounts of waste are related to population size, and therefore population growth. The inter-municipal companies vary in density of population, including cities of different sizes as well as scarcely populated areas, leading to different population growth (r_k^{pop}) among the municipalities. Data on population growth for different parts of Central Norway are provided by [7]. Population projections (*POP*) are calculated for the different inter-municipal companies (*k*) separately and for each year (*t*), assuming a steady growth rate (r_{wt}^{cap}) based on the recent years trends for the entire time span.

There has been increasing focus on waste management in the recent decade, and it is of primary interest to decouple the growth in waste generation from the growth in the economy and welfare. Still, the trend for the recent years indicates a further growth in the amount of waste. The growth in waste generation for the next couple of decades are assumed to follow the trends for the recent years. Projections concerning waste are based on actual numbers for the different municipalities and inter-municipal companies of Central Norway [4]. Projections are made for municipal waste, waste from industry and commerce and special waste for each of the inter-municipal companies for the entire time span. The waste types (*wt*) consist of a range of waste fractions, denoted as *wf*. Some of those are better suited for incineration than others. The physical properties of glass and metal make these fractions more attractive for material recovery, while other materials are both harder to recycle in a cost-effective way and have a heat value which make them attractive for incineration purposes. Municipal waste and waste from industry and commerce are both divided into seven categories: organic waste, wood, cardboard and paper, plastics, textiles, glass, and metals. Waste types consist of these same waste fractions and are therefore combined as regular waste in further calculations.

Treatment options for waste are mainly landfills, incineration and material recovery. Landfills and incineration without energy recovery are the least desirable treatment options [1]. Distribution of the fractions to the different methods for waste treatment are based on national numbers [6]. This distribution is adjusted to the situation in Central Norway, since larger amounts of the waste are used for incineration purposes in this part of Norway than what is suggested by the national average. Numbers for the other end treatment options (*ET*) are reduced in accordance with the increased amount for incineration. **Eq. 1** shows the calculation of waste amounts (*WM*) of various waste fractions to end treatment options, determined by the fraction coefficient *F*, pr. year and for each municipality, and also the origin with regard to waste type.

$$WM_{wt,wf,et,k,t} = POP_k^0 \cdot (1+r_k^{pop})^t \cdot WM_{wt,k}^{cap} \cdot (1+r_{wt}^{cap})^t \cdot F_{wf,wt} \cdot ET_{wf,et} \quad \forall wt, wf, et, k, t \tag{1}$$

For each municipality and year the amount that can be incinerated is found by summing over waste type and waste fraction. **Fig. 1** displays the projection of waste amounts, separated for different end treatment options for the region of Central Norway, with 2002 as the base year. The projections are based on recent trends. No scenarios about policy changes are included.

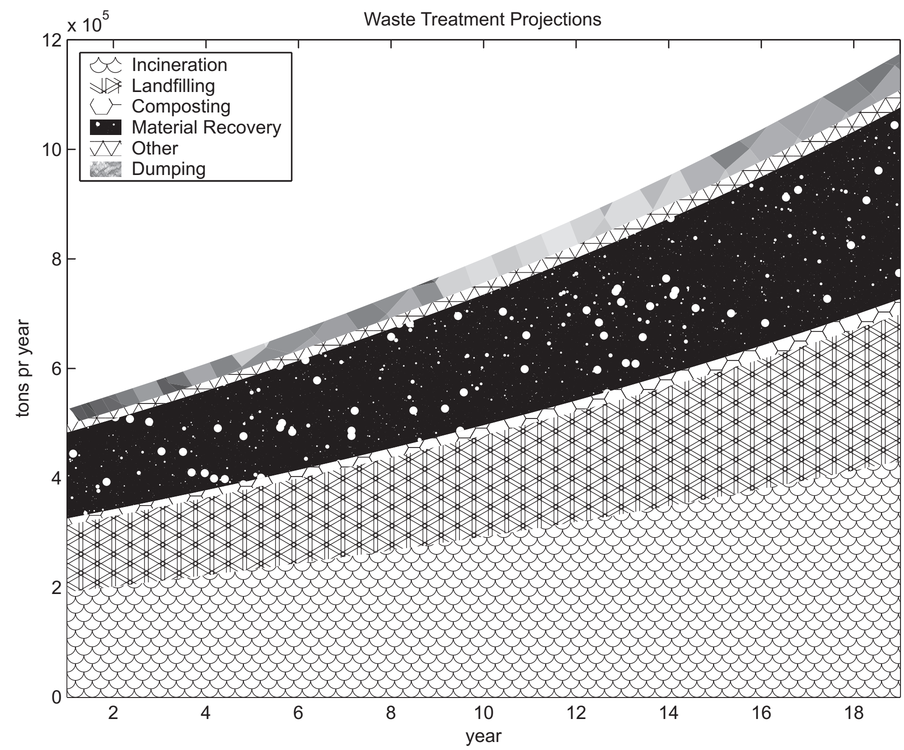

Fig. 1: Projected waste amounts for Central Norway, distributed on treatment alternatives for the period 2002–2020 [4,7]

As shown in Fig. 1 the waste generation is expected to increase substantially.

3 District Heating Potential

Having established the waste sources, potential sizes of sinks can be estimated. District heating systems are not very common in Norway and account for only about 2% of the energy delivery for heating purposes, although the number is rising. In Sweden and Denmark district heating supplies, respectively, 50% and 35% of heating energy [10]. The main reason for this is the historically low electricity cost and the low population density, which favored electric resistance heating. Until recently, there were no governmental initiatives to get out of this technology lock-in.

The potential energy output depends on the waste available for incineration, and so the waste projections give the energy potential from waste for the inter municipal companies. Scenario C consists of fewer and larger incineration plants, giving a higher energy output for the locations, which in turn calls for a higher heating demand in the vicinity of the plants. For the scenarios to be realistic, it is therefore necessary to investigate whether the heating demand in each area is sufficiently large in relation to the potential output from the incineration plants. This demand is computed for the different inter-municipal companies and compared to the waste projections.

There is a diversity of building types (bt) with different characteristics, leading to different heating demands. Actual numbers of buildings are obtained from [8] for the different parts of Central Norway and includes the following building types; single houses, chained houses, high houses, industrial and storage buildings, office and commercial buildings, travel and communication buildings, hotels and restaurants, research, education and culture buildings, hospitals and health institutions, prisons and military facilities. Heating demand is related to the floor area of different building types, and average areas (*AV*) for building types are found in [9], along with the annual growth rate of the floor area for the individual building types. Combining these gives projections of the total area of buildings for the years up to 2020. Conversion to district heating is not applicable for all buildings in the region, so only those prepared for water distribution of heat are regarded as potential customers for a district heating system. The percentage of buildings with water heating differs for the types of buildings. Population patterns determine the location of buildings and some are situated in areas not suitable for construction of district heating systems. 50% of the potential customers utilizing water heating are assumed to be located in areas where they will be considered as potential customers, a share denoted as L in equation 2. The share of new buildings prepared for water heating (*N*) is 30% [11]. Heating demand is related to the floor area of different building types. This means that first the number of existing buildings (*BLD*) of various types regarded as potential customers (*APC*), and their corresponding area, has to be found for each municipality in 2002. For the projections of heating demand, the floor area of expected new buildings (*AR*) of various types regarded as potential customers has to be found as well, with r^{area} as the growth rate in average area for different building types. Knowing exist-

ing and expected area potentially heated by district heating, the total area of various building types can be found pr. year and for each municipality.

Knowing the heating area, heat demand (*HD*) is determined by heat demand per unit area (*P*) for the various types of buildings. Heat demand per unit area is not the same for the building types and heating demand for each type has to be calculated before total heating demand within the municipality is found. The calculation of heat demand through calculation of potential heating area is demonstrated in **Eq. 2**.

$$\begin{aligned} HD_{bt,k,t} &= APC_{bt,k,t} \cdot P_{bt} \\ &= [BLD_{bt,k}^{2002} \cdot L \cdot AV_{bt} + AR_{bt,k,t}^{0} \\ &\quad \cdot (1 + r_{bt}^{area})^t \cdot L \cdot N] \cdot P_{bt} \quad \forall bt, k, t \end{aligned} \tag{2}$$

Summing over building types provides total heating demand (*THD*) pr. year for each municipality.

Projections of waste amounts together with heat demand for potential customers in the inter-municipal companies in Central Norway constitute the foundation for localization and scale of sinks, as district heating plants. **Table 1** shows waste amounts as of 2002. Municipal waste and waste from industry and commerce will be incinerated in the same plants, and are denoted as regular waste (*CP*) to distinguish it from special waste (*S*).

Table 1: Waste amounts and energy potential

Waste type	Waste amount (tons)	Energy potential (GWh)
CP	177,100	409
S	106,900	266

The potential energy production is calculated for comparison with energy potential, using average heating values for waste [12,13]. A first law efficiency of 75% is used for the incineration plants [1,14]. In Scenario L the special waste will be incinerated in district heating plants dedicated to this type of waste. The amount of waste is the same for both scenarios, but special waste is not utilized for local incineration within the region in Scenario C. Energy potential from regular waste therefore refers to Scenario C, while for Scenario L it is comprised of both regular and special waste, indicating an energy potential of 675 GWh. Calculation of heat demand equals to 4,767 GWh, which indicates that the potential customer base is more than sufficient compared to the amounts available for incineration. The energy potential is 8.5% of the heating demand in the region for Scenario C and 14% for Scenario L. This conclusion is further supported by estimations of total heating demand in Central Norway, regardless of potential customers, which is calculated to 20,313 GWh. Potential heat output is low compared to the total demand. These findings also hold when looking at the numbers from Table 1 for each inter municipal company separately.

4 District Heating Plants

The number and sizes of sinks, as well as their localization, varies greatly between the scenarios. The need for incineration capacity is larger for Scenario L since the special waste will be taken care of within the region as well. Construction of plants will take place in 2002 and 2010. Plants built in 2002 must therefore meet the capacity need for the period up to 2010, while additional plants built in 2010 have to meet capacity need for the period up to 2020. Increasing demand for incineration capacity will be met with additional plants, and not by expansion of existing ones.

Scenario C includes three facilities already in operation. A large-scale incinerator is present in the city of Trondheim, Norway's third largest city. This incinerator has a grate furnace and primary and secondary chambers. In southern parts of Norway organic special waste is incinerated in an industrial cement oven, while inorganic special waste is treated in a landfill specially designed for this purpose. Because these existing facilities do not satisfy the demand for incineration capacity, Scenario C contains 3 other incineration plants for the period from 2002 to 2010, increasing to a total of 8 in the last decade. These plants are based on technology from Energos ASA and are small scale grate furnace incinerators with primary and secondary chambers. This technology is only suitable for incineration of regular waste. Pre-treatment of the waste is required. Capacity of most incinerators in Scenario C is approximately 40,000 tons per year.

Scenario L has 14 incineration plants for regular waste and 3 for special waste for the first period, rising to 21 and 5, respectively, for the second period. Capacity ranges from 5,000 to 40,000 tons per year for plants dedicated to the incineration of regular waste, with capacities of about 15,000 tons as the most common size. These incinerators use the same small-scale technology from Energos ASA as in Scenario C. Incineration of special waste also takes place in the region of Central Norway in Scenario L, but is centralized within the region since the costs for construction and operation of this type of plants is higher. Incineration capacity of these plants is therefore as high as 35,000 to 60,000 tons per year. This technology was developed by EnviroArc Technologies AS, and can handle both organic and inorganic special waste, as opposed to the other technologies. The technology uses a plasma arc gasifier, reaching very high temperatures, sufficiently to decompose the different compounds and hereby reducing the emissions of harmful substances otherwise produced by incineration of special waste. Pre-treatment of waste is required for these plants as well.

Table 1 described the energy potential from waste as well as the heating demand. The ratio of energy potential to heating demand changes when the distribution of waste to incineration plants are accounted for. Some of the companies will receive waste for incineration from companies without an incinerator in their area, raising the ratio of energy potential to heating demand. For all cases in both scenarios, the ratio is well below 1, indicating sufficient number and size of customers. Incineration plants are located where waste is produced to reduce the need for transportation. The dis-

tribution of waste flows (*WFL*) from sources to sinks, i.e. from the municipality where it is produced to the municipality of treatment, is performed as shown in **Eq. 3**. *WCM* is the waste destination matrix. Naturally, the source and the sink are the same for some flows, since a municipality acting as a sink also takes care of the waste produced within this municipality

$$WFL_{wt,k,k,t} = WCM_{k,k,t} \cdot WM^{inc}_{wt,k,t} \quad \forall wt,k,k,t \tag{3}$$

Several sources deliver to the same sink, so total amounts delivered to each sink is found by summing over the sources. This gives the amounts of different waste types to each incineration plant for every year.

The path from sources to sinks are now traced, giving the basis for defining transportation need.

5 Transportation

Centralized vs. local incineration and treatment of waste results in great differences regarding transportation need. The initial collection of waste within each inter municipal company is the same for both scenarios and is therefore not accounted for. Also, the transportation of waste residues from incineration is not included, since the differences between the scenarios are very small with respect to this, and the contributions to the total results are negligible. This implies that the distances and amounts calculated relate to transportation of waste to the incineration plants. Trucks are used for this transportation. From the calculation of waste flows from sources to sinks, transportation need (*TR*) is found using **Eq. 4**, with distances between sources and sinks (*DST*) [15,16].

$$TR_{wt,t} = \sum_{k,k} WFL_{wt,k,k,t} \cdot DST_{k,k} \quad \forall wt,t \tag{4}$$

Knowing the transportation required for each waste flow, the total transportation need for each waste type is found for every year by summing up all transportation of regular waste and all transportation of special waste.

Table 2 shows the total cumulative amount of tonkilometers (tkm) for the scenarios, the ratio of transportation for the scenarios as well as the transportation related to each waste type, i.e. regular and special waste.

Special waste accounts for 37% of the total waste amounts for incineration, while transportation of this is by far the most dominating contributor to the total transportation need in both Scenario C and L. Transportation of special waste accounts for 79% of all transportation in Scenario C, and 92.5% in Scenario L.

Table 2: Transportation need (tkm)

Transportation	Scenario C	Scenario L	Ratio
Total	2.55×10^9	2.76×10^8	9.2
CP	5.36×10^8	2.07×10^7	25.9
S	2.01×10^9	2.55×10^8	7.9

The reason for this is obviously the longer distances to plants for treatment of this type of waste. In Scenario C special waste will be transported out of the region of Central Norway to facilities in southern parts of Norway, while the regular waste is incinerated within the region. Both regular and special waste are incinerated within the region in Scenario L, but the share of transportation associated with special waste is even more dominating here. This is due to a very high degree of local incineration of regular waste, with most inter municipal companies having an incinerator, while the more costly incineration of special waste is centralized within the region.

The ratios of transportation between the scenarios show significant differences for both regular and special waste. Total transportation need in tkm is 9.2 times larger for Scenario C, 25.9 times larger for regular waste and 7.9 times larger for special waste.

6 Life-Cycle Impact Assessment

The main purpose of this study is to assess and evaluate the potential environmental impacts of a strategy of centralized waste incineration vs. local incineration, using LCA-methodology. All waste has to be accounted for in every year for the period 2002–020 in both scenarios, i.e. the same functional unit. The life cycle assessment is performed using SimaPro software and the assessment method used is the CML2 method [17]. This assessment method measures midpoint results, which are the desired outcome for this study. Processes included are incineration and treatment of waste, transportation and construction of incineration plants. The impact assessment consists of 7 impact categories, denoted *ipc*; global warming (*GWP*), aquatic fresh water toxicity (*FAETP*), aquatic sea water toxicity (*MAETP*), terrestrial toxicity (*TAETP*), photochemical oxidation (*PCOP*), acidification (*AP*) and eutrophication (*EP*).

Waste amounts incinerated by each technology (tec) and in each location (*IPL*) need to be calculated to assess the environmental impacts from incineration, plant construction and transportation. Plant operation impacts are different for the various treatment technologies, so waste amounts for each technology (*IPW*) are found using **Eq. 5**.

$$IPW_{wt,tec,t} = \sum_{k} IPL_{tec,k,t} \cdot WFL_{wt,k,t} \quad \forall wt,tec,t \tag{5}$$

The inventories for the construction of incinerators are calculated using environmental input-output analysis. Input-output analysis was pioneered by Leontief, described in [18]. An extension of this work to explore environmental repercussions in the economy was first presented in [19]. Recommended base literature on input-output analysis is provided by [20].

Plant construction costs (*IPC*) vary for the different technologies, not only because of differences in size, but also due to technology costs. Plant construction impacts (*PCI*) for each technology are found from matrices describing emissions pr. economic input and combined with matrices of assessment of these emissions, giving impacts for each

technology. A_{IO} is the input-outputmatrix, and by summing over k for the plant construction costs the demand for construction is found. By combining this in **Eq. 6**, total impacts from construction are found for each impact category and each year of construction, i.e. 2002 and 2010, from

$$PCI_{ipc,tec,t} = C_{CML2} B_{IO} (I - A_{IO})^{-1} \cdot \sum_{k} IPC_{tec,k,t} \quad \forall ipc, tec, t \tag{6}$$

where C_{CML2} is the assessment matrix and B the emission matrix.

Plant operation impacts (*POI*) are given pr. ton waste for the different incineration and treatment options, and by combining this with waste amounts for each treatment technology, total plant operation impacts are calculated according to **Eq. 7**.

$$POI_{wt,ipc,t} = \sum_{tec} (C_{CML2} B_{tec}) \cdot IPW_{wt,tec,t} \quad \forall wt, ipc, t \tag{7}$$

All special waste is incinerated with energy recovery in Scenario L, while this is the case for only 5% of the amounts in Scenario C. Energy, as heat, equal to incineration of the remaining 95% therefore has to be added to give the same energy output for both scenarios, according to the functional unit. This energy is provided by natural gas and total impacts resulting from burning of natural gas (*TNGI*) are given by **Eq. 8**, for all years

$$TNGI_{ipc,t} = C_{CML2} \cdot B_{LCA} (I - A_{LCA})^{-1} y_{NG} \quad \forall ipc, t \tag{8}$$

where A_{LCA} is the LCA-matrix, y_{NG} the demand vector and M the number of kWh needed to cover up the difference in heat production between the scenarios.

Waste flows between municipalities cause impacts from transportation of these. Total impacts (*TI*) from transportation can be assessed for the waste types for all years with **Eq. 9**.

$$TI_{wt,ipc,t} = C_{CML2} B_{LCA} (I - A_{LCA})^{-1} y_{trsp} \cdot TR_{wt,t} \quad \forall wt, ipc, t \tag{9}$$

With the total results from the impact assessments related to the different processes, a total impact assessment (*TEI*) for each impact category and each year can be given for both scenarios, using **Eq. 10**.

$$TEI_{ipc,t} = TNGI_{ipc,t} + PCI_{ipc,t} + \sum_{wt} (TI_{wt,ipc,t} + POI_{wt,ipc,t}) \quad \forall ipc, t \tag{10}$$

These aggregated results constitute the basis for comparison of the environmental performance of the two scenarios, as well as the relative importance of the contributions from the different processes.

7 Costs

The technology for small scale incineration is available today, and heat demand in the region is also sufficient. Rough cost estimates for construction and operation of the scenarios are calculated to see if such a solution is realistic from an economical point of view. Costs for construction of incineration plants, plant maintenance- and operation costs and transportation of waste are included. Incineration in small-scale facilities requires some pre-treatment of waste in the form of shredding. Costs related to this are also accounted for. Costs for natural gas for heat production in Scenario C are added. Scenario C has three facilities which are in operation today, one for incineration of organic special waste, one for treatment and neutralization of inorganic special waste and one large scale incinerator for municipal waste. Since these are in operation today, construction costs are not included. However, the existing incinerator for municipal waste is expanded to increase the capacity, and costs for this expansion are included.

Costs are calculated for the entire time span, 2002 to 2020, adding up to a total system cost for the scenarios. Depreciation of buildings is taken into consideration, and the total cumulated system costs for all years are presented as present values today. The operating time of incineration plants are estimated to 20 years, with a depreciation factor a of 0.1. The costs of demolition of plants built in 2002 are assumed to equal the remaining value of the plants in 2020. Plants constructed in 2010 have a remaining value (*RMV*) in 2020. **Eq. 11** provides these.

$$RMV_{k,tec}^{2020} = \frac{IPC_{k,tec}^{2002}}{(1+a)^{18}} + \frac{IPC_{k,tec}^{2010}}{(1+a)^{10}} \quad \forall k, tec \tag{11}$$

Total system costs are discounted for the respective years and presented as present values (*TDSC*), using **Eq. 12**

$$TDSC = \frac{\sum_{k,tec,t} IPC_{k,tec,t}}{(1+r)^t} + \frac{\sum_{wt,t} TRC_{wt,t}}{(1+r)^t} + \frac{\sum_{k,tec,t} OPRC_{k,tec,t}}{(1+r)^t} \frac{\sum_{k,tec,t} PREC_{k,tec,t}}{(1+r)^t} + \frac{\sum_t NGC_t}{(1+r)^t} - \frac{\sum_{k,tec} RMV_{k,tec}^{2020}}{(1+r)^t} \quad \forall wt, k, tec, t \tag{12}$$

where *TRC* is transportation costs, *OPRC* is operation costs, *PREC* is pre-treatment costs and *NGC* is natural gas costs. This gives the total cumulative costs for the scenarios, from which they can be compared, as well as the relative contribution from the different processes.

8 Results and Discussion

Results from the environmental impact assessment are calculated for each year and summed up to give cumulative results for the entire time span. **Fig. 2** shows cumulative results for the global warming potential for both scenarios, with 2002 as the base year.

For Scenario C, the central scenario, the contribution from natural gas for heating purposes is the dominating process for the global warming potential, followed by incineration of regular waste and transportation of special waste. Recall

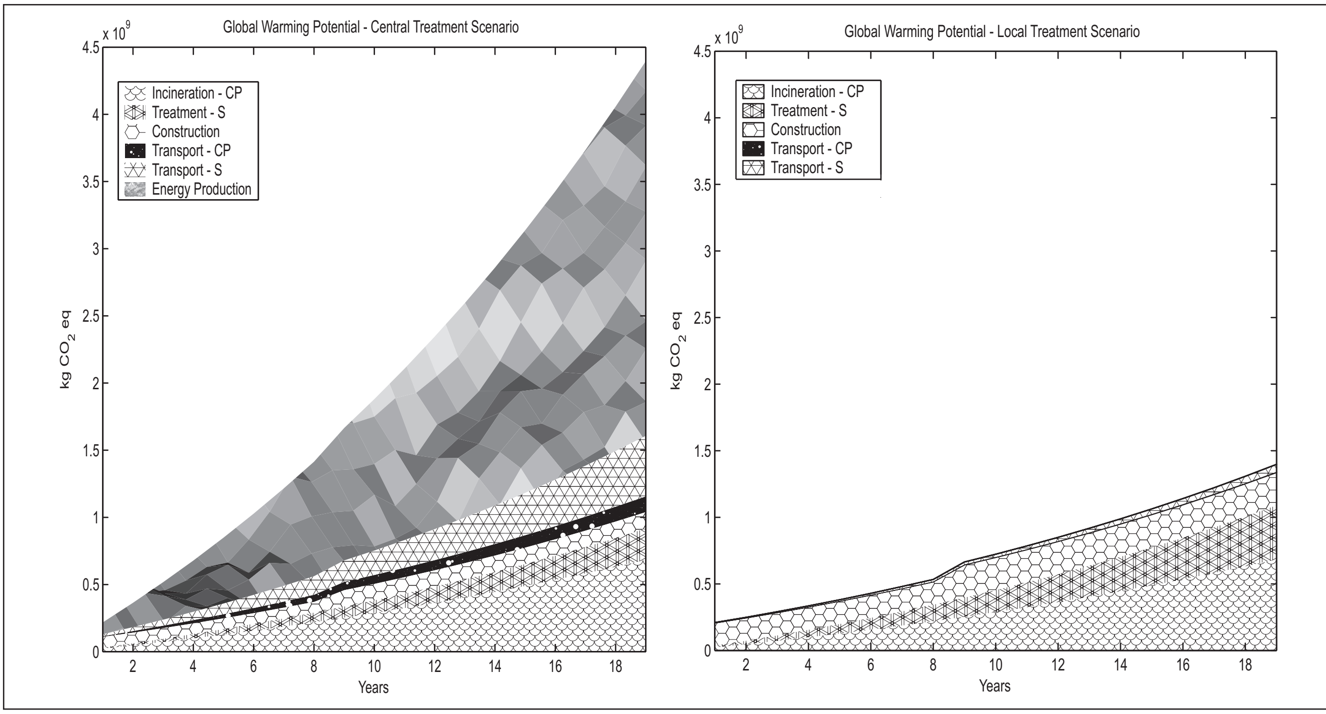

Fig. 2: Cumulative global warming potential for the period 2002–2020

from Section 6 that incineration of natural gas is added in Scenario C in order to fulfill the functional unit by providing the same energy output for both scenarios. Only fossil carbon is accounted for in the waste incineration, giving an emission rate of 133 kg CO_2 per ton waste. With an effective heating value of 9.25 GJ/ton, this gives approximately 14.4 tons CO_2 per GJ, compared to approximately 90 tons per GJ for incineration of natural gas, adjusted for boiler efficiency. Specific CO_2 emissions from natural gas are therefore approximately 6 times higher than for waste incineration, explaining the large difference displayed in Fig. 2. Transportation of special waste is a much larger contributor than transportation of regular waste due to the longer transport distances. The effects of plant construction are of minor importance for the cumulative results, but are important contributors in 2002 and 2010 when construction takes place. **Table 3** shows the largest and second largest contributing processes to each impact category for both scenarios.

As can be seen from Table 3, the contribution to total impacts from incineration of natural gas for heat production is not as dominating for the other impact categories as for the global warming, although it is the main contributor concerning photochemical oxidation and eutrophication, as well as the second most contributor to fresh water toxicity. Impacts related to special waste is dominating when looking at all impact categories on average. Transportation and treatment of this waste type are among the top contributors for most categories. Treatment of special waste is important for marine toxicity, acidification and photochemical oxidation, while the corresponding transportation plays an important part regarding toxicity categories, acidification and eutrophication. Transportation of regular waste, however, is not among the major processes for any impact category, even though it constitutes most of the total waste amounts. Incineration of regular waste contributes with considerable CO_2 emissions to the global warming potential, and is the major source of terrestrial toxicity, but is otherwise of minor importance.

For Scenario L, the local scenario, incineration of waste constitutes the highest CO_2 emissions and therefore contributes

Table 3: The first and second most important processes for cumulative results for the period 2002–2020

	Scenario C		Scenario L	
Impact Category	**1st Contribution**	**2nd Contribution**	**1st Contribution.**	**2nd Contribution**
GWP	Incineration NG	Incineration CP	Incineration CP	Incineration S
FAETP	Transportation S	Incineration NG	Transportation S	Construction
MAETP	Treatment S	Transportation S	Incineration S	Transportation S
TAETP	Incineration CP	Incineration S	Incineration CP	Incineration S
PCOP	Incineration NG	Treatm. S	Incineration S	Construction
AP	Treatment S	Transportation S	Incineration S	Incineration CP
EP	Incineration NG	Transportation S	Incineration CP	Incineration S

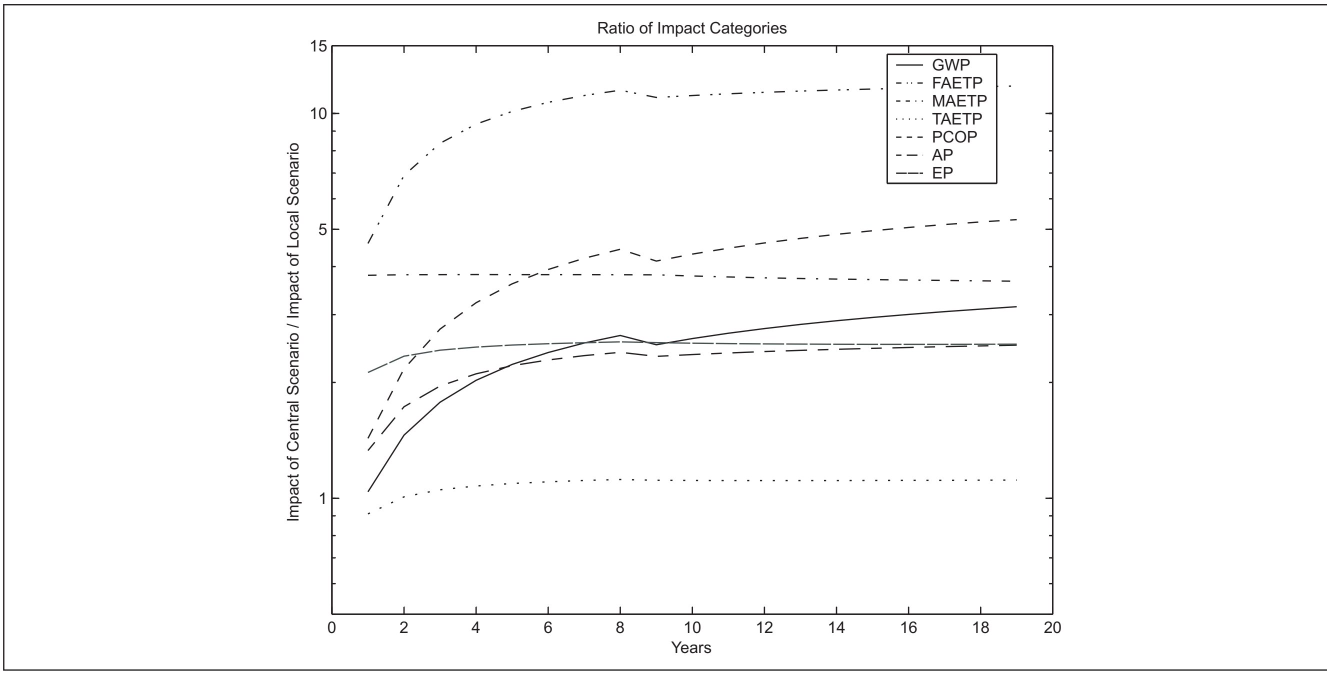

Fig. 3: Ratio between Scenario C and L for cumulative results and all impact categories for the period 2002–2020

the most to the global warming potential. Incineration of regular waste has the highest impact for this category, which is mostly due to the larger amount of waste being incinerated. Waste incineration is the major contributor for all but one impact category, but the relative importance of special waste incineration relative to regular waste incineration differ for the categories. Incineration is also the second most contributing process for several categories. Special waste incineration dominates for sea water toxicity, while the opposite is the case for terrestrial toxicity. The difference in importance between incineration of the two waste types are smaller for the other categories, more reflecting the difference in waste amounts. As in Scenario C, the impacts from transportation are mainly related to the special waste. Relative to waste incineration, transportation is still of minor importance, due to the great reduction in transport distances from Scenario C. Construction of incineration plants is a larger contributor in Scenario L because of a higher number of incinerators in this scenario. It is the second most important contributor for fresh water toxicity and photochemical oxidation.

The ratio between Scenario C an L are displayed in **Fig. 3** for all impact categories.

CO_2 emissions are quite similar for the first year, with Scenario C being somewhat higher. This difference rises steadily and ends with being more than 3 times as large for the centralized solution, when looking at the cumulative results. The use of natural gas for heat production is the dominating contributor to the CO_2 emissions, and without this contribution the difference would be much lower, with Scenario L having 83% of Scenario Cs global warming potential. With natural gas included, the local incineration solution is favored. Regarding cumulative results up to 2020, the local solution is preferred for all the other impact categories as well, as displayed in more detail in Fig. 3. However, there are great variation in magnitudes for the different impact categories. For the terrestrial toxicity potential, the ratio is just above 1, while the other extreme is the fresh water toxicity with a value of approximately 12. For the other impact categories, the ratio is in the area of 2.5 to just above 5, indicating that the local scenario is preferred from an environmental point of view.

The increases in the ratios are steeper for the years up to 2010 than for the last ten years. This is due to larger transportation need for this period. Impacts from incineration and treatment of waste are determined by the waste amounts, which are the same for both scenarios. This is not the case with the transportation. The transportation need is far greater for Scenario C and after construction of more incineration plants in 2010, the relative importance of transportation compared to the other processes are lower. This further expansion of incineration capacity in 2010 leads to a drop in the ratio between the scenarios for this year. The reason being a larger number of incinerators constructed in Scenario L.

Costs related to the different processes in the scenarios are estimated, and results are displayed as cumulative discounted costs in **Fig. 4**.

Summing up all costs for the two scenarios show that the local scenario is the most favorable from an economic point of view, although it has higher costs the first years. Total system costs for the entire period for Scenario L is about 83% of the costs of Scenario C. Without the need for natural gas to deliver the same heat output for the scenarios, Scenario C would be the preferred alternative when looking at total costs. The greatest differences are transportation of waste and construction of incineration plants. Construction is the main contributor to the costs in Scenario L, accounting for 45% of the cumulative costs, but only 18% for Scenario C. Construction costs are nearly twice as large for the local solution. For transportation the difference is even larger.

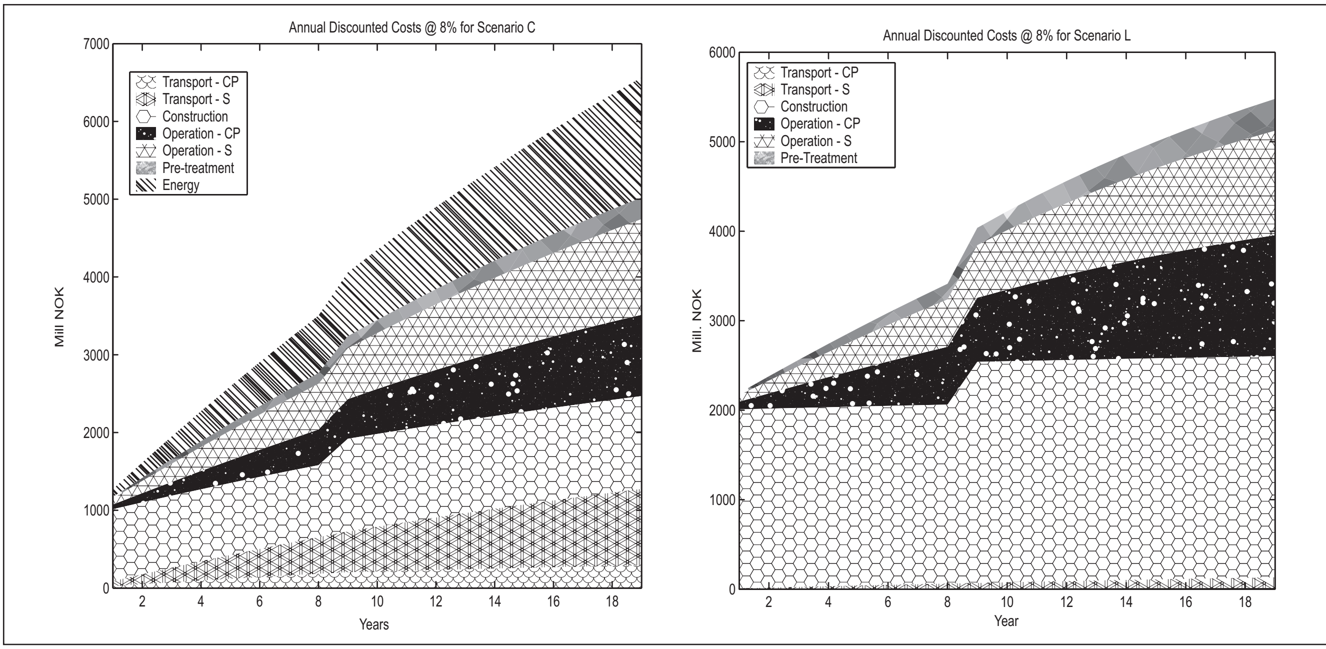

Fig. 4: Temporal distribution of net present value with discount rate of 8%

The combined costs for transportation of both regular waste and special waste contribute with nearly 20% of total costs in Scenario C, whereas the contribution is only about 2.5% for the local scenario. Pre-treatment is required for all waste in Scenario L due to the extensive use of small scale incinerators, increasing the costs. Operation costs is not significantly different with about 10% higher costs for the local solution due to more advanced and costly technology.

Fig. 5 shows the relationship between the costs for the scenarios for discount rates from 0% to 25%. Scenario L is favored for discount rates between 0% and 20%, while Scenario C is preferred for discount rates above 20%. The ratio becomes smaller for higher discount rates, indicating that the more important future costs are regarded the larger the difference between the scenarios will be.

9 Conclusion

A strategy of centralized incineration of waste for heat production in Central Norway is compared to a local strategy regarding potential environmental impacts for a time span of nearly two decades. The results show clearly that the scenario with local treatment in small incinerators, compared to the scenario of centralized treatment in large scale facilities, is the most favorable for all evaluated impact categories. The differences in cumulative impact potential vary between 2.5 to about 5 for most impact categories, indicating significantly higher

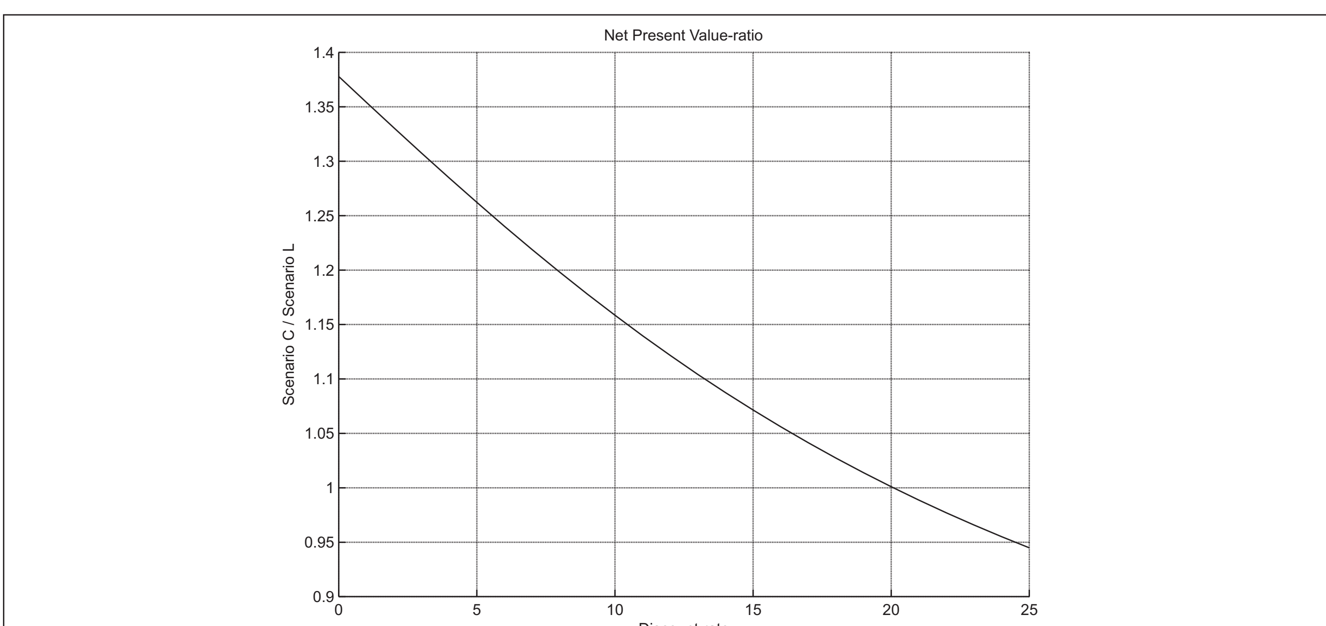

Fig. 5: Net present values ratio using different discount rates

emissions from the centralized scenario. Transportation and fossil heat production have high impacts compared to waste incineration, so systems should be designed to minimize transport and maximize useful heat production. Long transportation distances related to special waste is a major contributor to the transportation impacts. Estimates for cumulative costs also favor a local incineration scenario.

10 Legend

A_{IO}	Input/Output-matrix
A_{LCA}	LCA-matrix
AV	average area building types
APC	area potential customers
AR	area
B	emission matrix
BLD	number of buildings
C_{CML2}	assessment matrix
CP	municipal waste and waste from industry and commerce, i.e. regular waste
DST	distance
ET	end treatment
F	fraction coefficient
HD	heat demand
I	identity matrix
IPC	plant investment cost
IPL	incineration plant location
IPW	waste amount incinerated by different technologies
L	coefficient for location of potential customers
M	number of kWh as heat produced from burning of natural gas
N	coefficient for share of new building area regarded as potential customers
NGC	natural gas cost
NGI	natural gas impact
$OPRC$	operation cost
P	heat demand pr. area
PCI	plant construction impact
POI	plant operation impact
POP	population
$PREC$	pre-treatment cost
RMV	remaining value
S	special waste
$TDSC$	total discounted system cost
TEI	total environmental impact
THD	total heating demand
TI	transportation impact
$TNGI$	total natural gas impact
TR	transportation need
TRC	transportation cost
WCM	waste destination matrix
WFL	waste flow
WM	waste amount
WM^{inc}	waste amount incineration
WM^{cap}	waste amount pr. capita
a	depreciation factor
bt	building types
ipc	impact category
k	inter municipal company
r	discount rate
r^{area}	growth rate in average area
r^{cap}	growth in waste generation pr. capita
r^{pop}	population growth
t	year
tec	technology
wf	waste fraction
wt	waste type
x	demand vector

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